

Oligoaniline Assisted Dispersion of Carbon Nanotubes in Epoxy Matrix for Achieving the Nanocomposites with Enhanced Mechanical, Thermal and Tribological Properties*

Bin Chen^a, Jia Chen^{a,b}, Jing-yu Li^a, Xin Tong^b, Hai-chao Zhao^{b**} and Li-ping Wang^{b**}

^aSchool of Materials Science and Engineering, Shenyang University of Chemical Technology, Shenyang 110142, China

^bKey Laboratory of Marine Materials and Related Technologies, Zhejiang Key Laboratory of Marine Materials and Protective Technologies, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, China

Abstract A critical challenge for initiating many applications of the carbon nanotubes (CNTs) is their dispersion in organic solvent or in polymer melt. In the present study, we described a novel strategy for fabricating carbon nanotubes (CNTs)-reinforced epoxy nanocomposite by utilizing aniline trimer (AT) as the noncovalent dispersant. Tensile testing showed that the tensile modulus of the CNTs-reinforced epoxy composites was considerably improved by adding a small amount of AT functionalized CNTs. Additionally, the as-prepared CNTs-epoxy nanocomposites exhibited superior tribological properties with much lower frictional coefficients and wear rates compared to those of neat epoxy resin. The well dispersed AT-functionalized CNTs in epoxy matrix played an important role in enhancing the mechanical properties, as well as acting as a solid lubricant for improving the tribological performance of epoxy/CNTs nanocomposite.

Keywords Carbon nanotubes; Epoxy; Mechanical; Tribological; Nanocomposites

INTRODUCTION

Carbon nanotubes (CNTs) are one dimensional carbon materials with remarkably optical, electrical and mechanical properties, as well as excellent chemical and thermal stability^[1]. These properties have inspired interest in using CNTs as fillers for fabrication of polymer nanocomposite with advanced properties^[2–5]. Among polymer-related nanocomposites, epoxy based resins are one of the most commonly used materials for coatings, adhesives, electronics packaging, constructions, aircraft, and many other industrial applications^[6–8]. Incorporation of CNTs into epoxy-based polymers holds the promise of imparting the composite materials with superior properties such as improved strength, anticorrosion properties, thermal and electric conductivity, and wear resistance^[4, 9–12]. In general, the fabrication of epoxy/CNTs composite could be achieved by several methods including solution blending, melt compounding, and *in situ* polymerization^[13, 14]. However, with strong π - π stacking interactions and intrinsic van der Waals forces, CNTs tend to hold together as bundles and are difficult to disperse in polymer solution or melt^[15]. Therefore, the disaggregation of CNTs bundles and control of interfacial interaction between nanotubes and epoxy matrices are critical challenges to promote

* This work was financially supported by “One Hundred Talented People” of the Chinese Academy of Sciences (No. Y60707WR04), National Basic Research Program (973 Program, No. 2015CB654705) and Natural Science Foundation of Zhejiang Province (No. LY16B040004).

** Corresponding authors: Hai-chao Zhao (赵海超), E-mail: zhaohaichao@nimte.ac.cn

Li-ping Wang (王立平), E-mail: wangliping@nimte.ac.cn

Received August 25, 2016; Revised September 8, 2016; Accepted September 15, 2016

doi: 10.1007/s10118-017-1911-z

extraordinary properties of CNTs.

Extensive research has been reported on development of dispersion technologies to enhance the wetting and reactivity of CNTs^[16]. One of the most effective methods for reducing agglomeration and increasing the interfacial interactions between CNTs and polymer matrices is the introduction of functional groups on carbon nanotube surface^[17]. For instance, Kharitonov *et al.* investigated the influence of fluorinated carbon nanotubes on the thermal and mechanical properties of epoxy resin composites. They found that insertion of fluorinated CNTs into a polymer matrix significantly increased the tensile strength, flexural strength, and glass transition temperature (T_g) as compared to unfilled epoxy resin^[18]. Jiang and coworkers investigated the effect of free organic groups in carbon nanotubes on glass transition temperature of epoxy matrix composites. Both simulation and experimental results revealed that T_g of pristine CNTs/epoxy composites is higher than that of pure epoxy resin, while T_g s of the composites containing CNTs with $-\text{COOH}$ and $-\text{OH}$ group are lower than those of pristine CNTs based composites due to large interphase between CNTs and epoxy matrix^[19]. Weidt *et al.* developed a nonlinear computational model to predict the compressive response of epoxy/CNTs nanocomposites by considering van der Waals forces, perfect bonding and CNTs waviness^[20].

In general, aggressive chemical process is necessary for introduction of functional groups on CNTs, which might render structural defects and result in inferior properties of CNTs. Noncovalent functionalization of CNTs by using π -conjugated molecules represents another attractive approach to achieve dispersed CNTs without disturbing their graphite structures^[21]. Yuan *et al.* reported the synthesis of polyimide grafted bisphenol acrylate as a noncovalent dispersion of carbon nanotube. The as-prepared carbon tube reinforced cyanate ester/epoxy composite showed remarkably improved tensile modulus, strength, and toughness by addition of only 1 wt% CNTs^[22]. Sun and coworkers reported the dispersion of CNTs using pyrene containing polystyrene diblock polymers, resulting in the CNTs reinforced epoxy composites with significantly enhanced mechanical and electrical properties^[23]. A polyaniline coated CNTs/graphene “sandwich” hybrid reinforced epoxy composites remarkably improved the dielectric properties due to synergistic effect between polyaniline-CNTs-graphene^[24]. Fujigaya *et al.* described a strategy for reinforcing epoxy resin with much improved tensile strength and Young’s modules by using polybenzimidazole (PBI) as the glue to enable effective adhesion between CNTs and epoxy matrices^[25]. Fu and coworkers reported that the incorporation of CNTs/graphene oxide hybrid at a low content into an epoxy matrix has led to a significantly enhanced tribological performance because the graphene oxide improved the dispersion of carbon nanotube in epoxy matrix and greatly enhanced the adhesion between the carbon nanotube and epoxy matrix^[26].

In this study, we reported the synthesis of aniline trimer (AT) with end capped amines as noncovalent dispersant for CNTs. The aromatic nature of AT is expected to strongly interact with CNTs *via* π - π interaction and facilitate the CNTs dispersion, while the end capped amine groups enable reaction with epoxy matrices to form covalent bonds (Fig. 1). The interaction between AT and CNTs was investigated by UV-Vis, Raman spectra, and TEM, respectively. The tensile properties, thermal and tribological properties of CNTs reinforced epoxy composites were evaluated as a function of CNTs content.

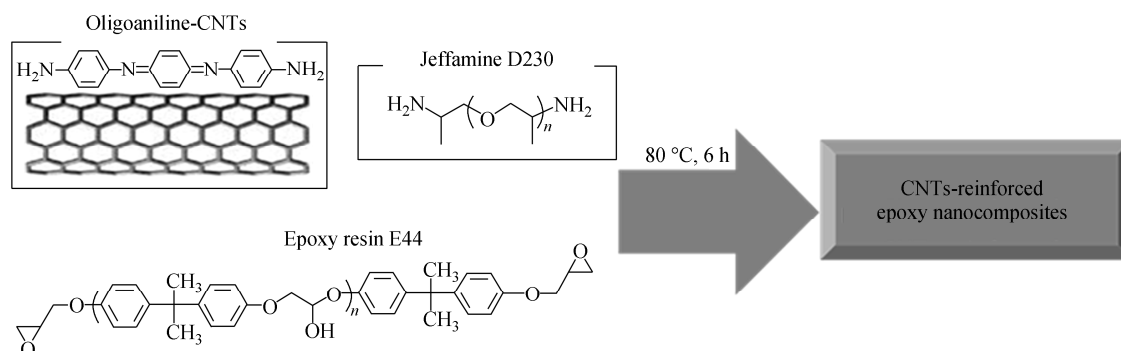


Fig. 1 Schematic diagram for preparation of CNTs-reinforced epoxy nanocomposites using oligoaniline functionalized CNTs

EXPERIMENTAL

Materials

Aniline and concentrated HCl were purchased from Sinopharm Chemical Reagent Shanghai Co. Ltd., China. *p*-Phenylenediamine sulfate, ammonium persulfate, tetrahydrofuran (THF), ethanol, *N,N*-dimethylformamide and ammonium hydroxide were purchased from Aladdin Industrial Corporation, and were used as received. Epoxy resin (E44) was provided by Jiangsu Sanmu (Group) Co. Ltd., China. Curing agent (Jeffamine D230) was purchased from Sigma-Aldrich. Multiwalled carbon nanotubes (CNTs) (Diameters: 10–50 nm, purity: 96%) were purchased from Beijing Boyu Gaoke New Materials Company.

Synthesis of Aniline Trimer (AT)

AT was synthesized in a similar manner as reported^[27, 28]. Aniline (5.56 g, 60 mmol) and *p*-phenylenediamine sulfate (8.87 g, 30 mmol) were first dissolved in 1.0 mol/L HCl solution (450 mL) in an ice salt bath. Then ammonium persulfate (13.62 g, 60 mmol) in 1.0 mol/L HCl solution (150 mL) was dropped into the above mixture. After the reaction was conducted for another 3 h, the resulting precipitate was collected by filtration. The solid product was washed with 10% NH₄OH solution (100 mL), and water (500 mL) for three times. Finally, the aniline trimer was dried at 40 °C in vacuum until constant weight. The yield was 9.2 g (64% yield).

Preparation of Epoxy/CNTs Nanocomposites

Typical epoxy/CNTs nanocomposite with 0.5 wt% CNTs was prepared according to the following procedure. AT (100 mg) was predissolved in 50 mL of THF, CNTs (200 mg) were then added to the AT solution and sonicated for 1 h. Epoxy resin E44 (32 g) was added to the above mixture, then the solvent was removed by rotary evaporator. Jeffamine D230 (8 g) was added to the epoxy/CNTs suspension and was degassed in the vacuum oven for 10 min. The mixture was then casted into Teflon mold at 80 °C for 6 h. For comparison purpose, the neat epoxy without CNTs was prepared in a similar way.

Characterization

UV-Vis spectra were recorded using a Lambda 950 UV-Vis spectrometer. Raman spectra were measured with a confocal Renishawin *via* Reflex Raman spectrometer. Field emission scanning electron microscope (SEM) type FEI Quanta FEG 250 was used to observe the morphology of epoxy/CNTs nanocomposites and worn surfaces. Transmission electron microscopy (TEM) images were obtained on a JEOL JEM2100 TEM instrument operated under a 200 keV acceleration voltage. Thermal analysis of the epoxy/CNTs nanocomposites was performed using Netisch thermogravimetric analyzer (TGA). The temperature ranged from 30 °C to 700 °C with a heating rate of 20 K/min under atmosphere to examine the thermal degradation behavior. The DSC measurement was made on a METTLERTOLEDO-TGA/DSC I under a nitrogen atmosphere.

Tensile test was performed under ambient conditions according to ASTM 638 using Universal Machine model INSTRON 5869 with the crosshead speed of 50 mm/min. Values were converted to stress-strain and the Young's modulus was calculated from the initial slope. Five identical samples were used and the average values were reported.

The wear tests were carried out using a MFT5000 pin-on-disk reciprocating friction and wear tester (Rtec, America). The tests were carried out by rubbing epoxy/CNTs nanocomposite with a ball of 316L steel (3 mm of diameter). The test environment was kept at a temperature of 25–30 °C. Sliding distance was 5 mm under a sliding frequency of 2 Hz and a load of 5 N.

RESULTS AND DISCUSSION

Dispersion and Characterization of AT Functionalized CNTs

It is well known that CNTs tend to aggregate and bundle together due to strong van der Waals interactions,

resulting in their poor solubility in organic solvent or in the polymer melt^[29]. Therefore, disaggregation of entangled CNTs in various solvents is crucially important to initiate their many applications. In this work, we described the dispersion of CNTs in various organic solvents using AT as noncovalent functionalization agent. Aniline trimer possesses electro-rich conjugated structure from the sp^2 hybridization derived from benzene rings and N atoms, facilitating the binding of AT to the surface of CNTs through strong π - π interactions. As shown in Fig. 2(a), direct dispersion of CNTs in organic solvents resulted in aggregation and precipitation, while CNTs formed stable dispersion in various organic solvents with the addition of AT after sonication. Observations of the dispersion of CNTs using SEM and TEM are shown in Figs. 2(b) and 2(c). The SEM image of the as-received CNTs showed that the CNTs packed into tangled networks due to strong van der Waals interaction, while the individual nanotubes with a diameter of *ca.* 20 nm could be exfoliated from the stacked networks with the aid of AT as verified by typical TEM image (Fig. 2c).

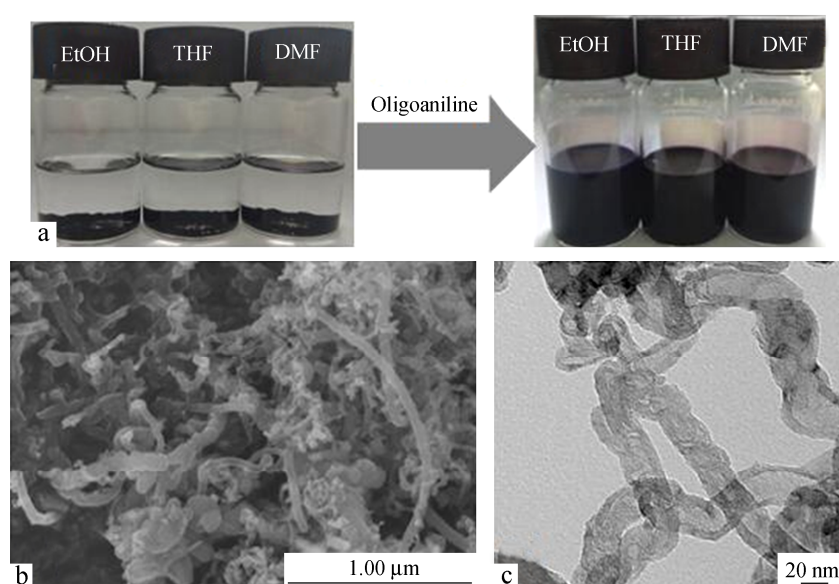


Fig. 2 Digital images of as-received CNTs and AT functionalized CNTs in organic solvents (a); SEM image of as-received CNTs bundles (b) and TEM image of individual CNTs nanotubes dispersed in THF with the aid of AT (c)

The Raman spectra were used to investigate the interactions between CNTs and AT. Figure 3 shows the Raman spectra of AT, CNTs and AT/CNTs hybrids, respectively. For AT, the bands at 1343, 1471, and 1593 cm^{-1} are associated with $\text{C}-\text{N}^+$ stretching, $\text{C}=\text{N}$ stretching, and $\text{C}=\text{C}$ stretching of quinoid units, which revealed the conjugated structure of AT^[30]. In the spectrum of CNTs, three typical bands were obtained based on the as-received CNTs bundles. The band at 1346 cm^{-1} (D band) is assigned to disordered carbons of CNTs, and the band at 1571 cm^{-1} is related to the in-plane vibration of the $\text{C}-\text{C}$ bond (G band), while the band at 2697 cm^{-1} is attributed to the overtone of the D band^[31]. Apparently, the characteristic bands of CNTs are shifted to 1347, 1579 and 2694 cm^{-1} , respectively, which are attributed to the favorable interaction between CNTs and aromatic of AT. This π - π interactions can also be verified by UV-Vis spectroscopy as shown in Fig. 4. The absorption peaks at 284 and 582 nm are attributed to the π - π transition of benzene unit and quinone ring in AT^[32], respectively. These absorption peaks of AT/CNTs hybrid shifted to 288 and 581 nm, respectively, demonstrating the π - π interaction between AT and CNTs.

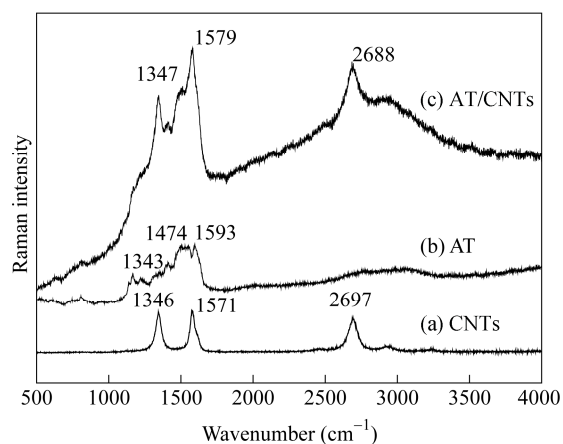


Fig. 3 Raman spectra of as-received CNTs (a), AT (b) and AT/CNTs hybrids (c)

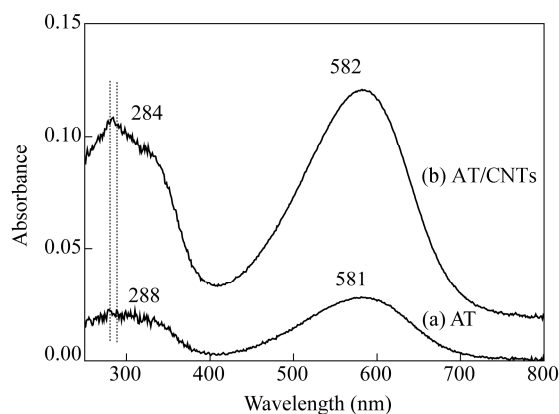


Fig. 4 UV-Vis spectra of AT (a) and AT/CNTs hybrids (b)

Preparation and Thermal Properties of CNTs Reinforced Epoxy Nanocomposites

A series of CNTs reinforced epoxy composites with various CNTs contents (0.25%, 0.5%, 1% and 2%, weight ratio) were prepared by curing reaction with epoxy resin (E44), Jeffamine D230 and AT functionalized CNTs. For comparison, neat epoxy resin was prepared in a similar way to AT-epoxy/CNTs composite. The morphology of CNTs in epoxy composites was investigated by SEM and TEM. Figures 5(a) and 5(b) show the typical SEM image of fracture surface of pure epoxy resin and 0.25% epoxy/CNTs composites. Neat epoxy resin exhibited a typical oriented fracture patterns initialized from the cracks, while CNTs-reinforced showed completely different morphology because CNTs disturbed the cracks and crack propagation. A representative TEM image of 0.25% epoxy/CNT composite revealed that the AT effectively facilitated CNTs to be dispersed in epoxy matrices and individual CNTs were found randomly distributed in epoxy matrix with the aid of AT (Fig. 5c).

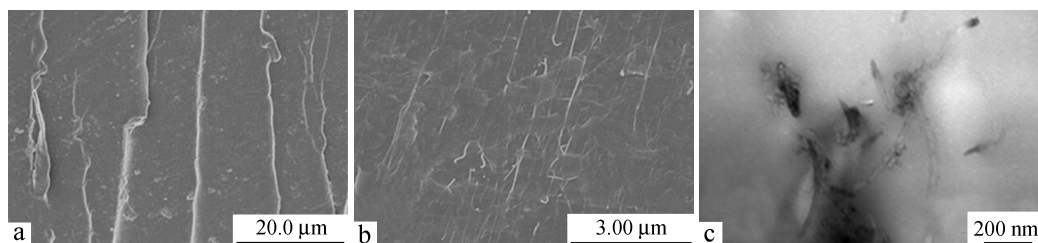


Fig. 5 SEM images of fracture surface of neat epoxy (a) and 0.25% CNTs/epoxy nanocomposites (b), and TEM image of 0.25% epoxy/CNTs nanocomposite (c)

The effects of CNTs on the thermal properties of epoxy composite were evaluated by DSC and TGA. Figure 6 depicts the DSC thermograms for pure epoxy and CNTs reinforced epoxy composites, displaying their glass transition temperature around 72–85 °C. The epoxy/CNTs composites exhibited lower T_g s compared with neat epoxy, probably because the structure of epoxy-amine crosslinked matrix was changed due to induction of AT into polymeric network^[33]. TGA curves for neat epoxy and epoxy/CNTs composites with different CNTs contents are shown in Fig. 6(b), from which the initial and final decomposition temperature of specimens can be obtained. All composites and neat epoxy exhibit similar degradation with two degradation steps. The initial decomposition temperature is around 375 °C due to degradation of the macromolecular chains; and another at around 550 °C probably is attributed to degradation of char residue.

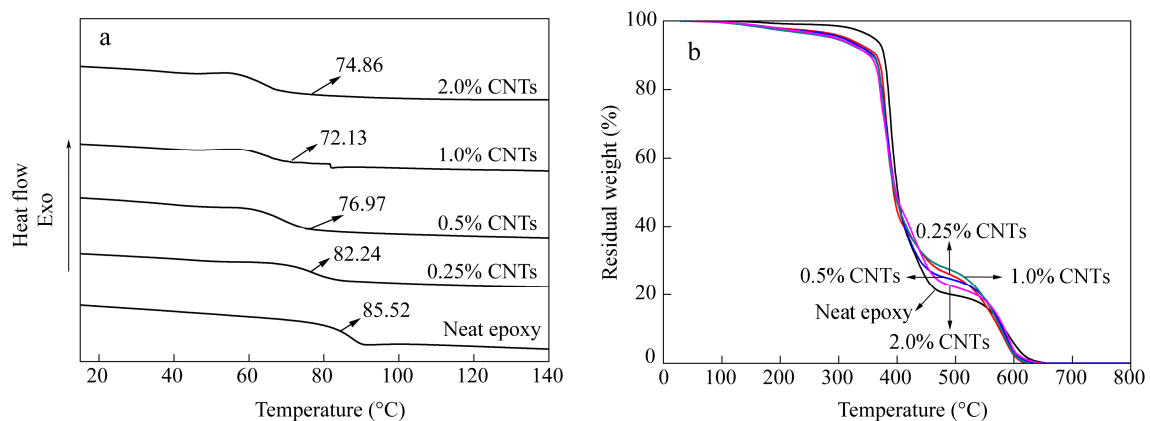


Fig. 6 DSC (a) and TGA (b) curves of epoxy/CNTs nanocomposites with different contents of CNTs

Mechanical Properties of Epoxy/CNTs Composites

Figure 7 presents tensile strength curves and elongations at break for the composites with different CNT contents, from which the tensile strength and Young's modulus were determined and are summarized in Table 1. Neat epoxy exhibited a tensile strength of 52.52 MPa, tensile modulus of 1.320 GPa, and elongation at break of 6.57%. The tensile strength of epoxy/CNTs composites decreased slightly, while the modulus increased considerably with the addition of CNTs. Especially, the modulus of 0.25% epoxy/CNTs composite improved to 1.593 GPa, which was increased by 21% compared to that of neat epoxy, demonstrating the best mechanical performance. The increase in modulus was obviously owing to the reinforcement effect of CNTs in the nanocomposites. On the other hand, a slight decrease in tensile strength was probably due to the weak boundaries between the CNTs and limited interfacial interaction between CNTs and epoxy matrix^[34]. Many studies have indicated that the tensile modulus of polymer/CNTs nanocomposites increased in comparison with pure polymer, while most of randomly dispersed CNTs usually resulted in a moderate or no improvement of

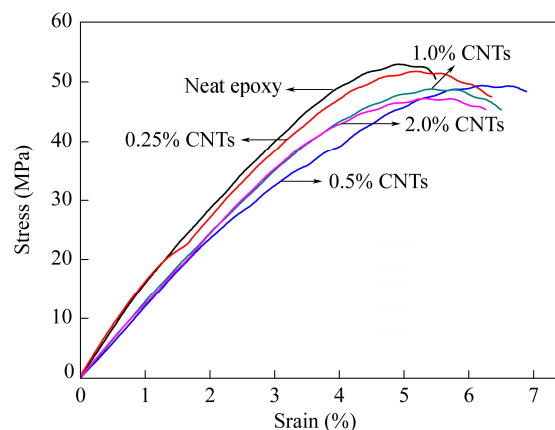


Fig. 7 The stress-strain curves of epoxy/CNTs nanocomposites

Table 1 Mechanical properties of CNTs-reinforced epoxy nanocomposites

CNT contents (wt%)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
0	52.52 ± 2.81	1.320 ± 0.099	6.57 ± 0.91
0.25	51.47 ± 1.54	1.593 ± 0.148	8.01 ± 1.68
0.5	50.22 ± 4.03	1.472 ± 0.238	7.48 ± 1.73
1.0	49.20 ± 4.03	1.455 ± 0.182	7.28 ± 1.44
2.0	47.40 ± 1.29	1.370 ± 0.207	6.81 ± 1.05

tensile strength, especially for polymers/CNTs composites without interfacial bonding^[35–37]. Therefore, homogeneous dispersion of CNTs and good interfacial bonding between CNTs and polymer matrices are both necessary for enhancing the mechanical properties of polymer composites.

Effects of CNTs on Tribological Behavior of Epoxy Nanocomposite

The tribological behavior of CNTs reinforced epoxy nanocomposites was investigated using a MFT5000 pin-on-disk reciprocating friction and wear tester. Figure 8 shows the variations of friction coefficient and wear rate under a sliding frequency of 2 Hz and a load of 5 N with various CNTs contents. It can be seen that the friction coefficient of epoxy/CNTs composites decreased with the addition of CNTs (Fig. 8a). Notably, the friction coefficient of 0.25% epoxy/CNTs nanocomposite decreased by 31% with respect to the neat epoxy, which is because the highly dispersed CNTs in epoxy matrix acted as solid lubricants, resulting in formation of a solid transfer film on the counterpart^[38].

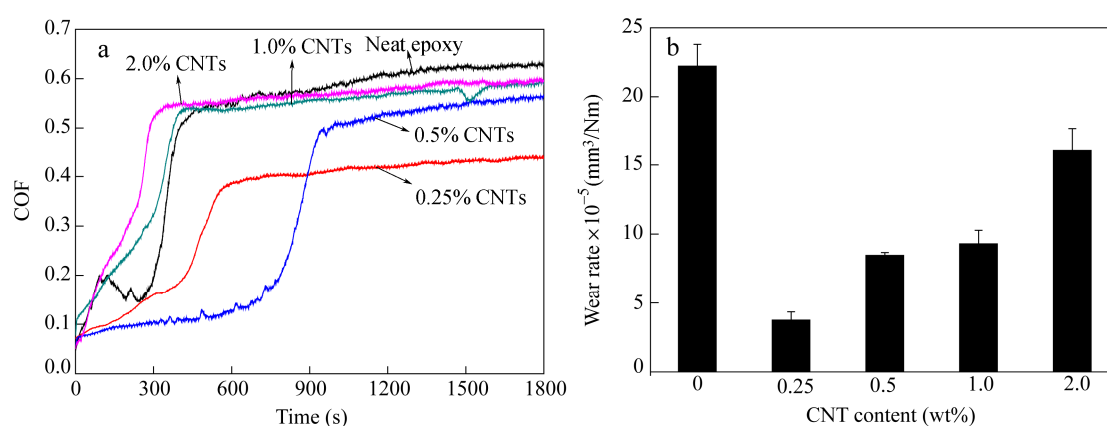


Fig. 8 The friction coefficient (a) and wear rate (b) of CNTs-reinforced epoxy nanocomposites

While the wear rate of pure epoxy is $2.2 \times 10^{-4} \text{ mm}^3/\text{Nm}$, the wear rates of epoxy/CNTs composites with 0.25%, 0.5%, 1% and 2% CNTs decreased to 3.8×10^{-5} , 8.5×10^{-4} , 9.3×10^{-4} and $1.6 \times 10^{-4} \text{ mm}^3/\text{Nm}$, respectively (Fig. 8b). The enhanced wear resistance of epoxy/CNTs nanocomposites can be explained by the improved mechanical properties of the composites and well-dispersed CNTs in epoxy matrix. Incorporation of CNTs into epoxy matrix significantly reduced plastic deformation and exfoliation of epoxy resin^[39].

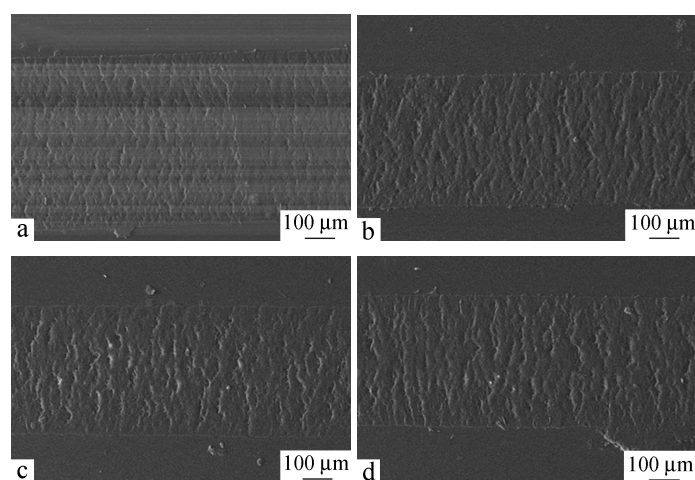


Fig. 9 SEM images of worn surface of neat epoxy (a), epoxy/CNTs nanocomposite with 0.25% (b), 0.5% (c) and 1% (d) CNTs

The worn surfaces of the neat epoxy, and epoxy/CNTs nanocomposites with 0.25%, 0.5% and 1% CNTs were investigated as shown in Fig. 9. It can be clearly seen that the neat epoxy showed larger wear width and much more blocky fragments compared to epoxy/CNTs composites. The abrasion mechanism of epoxy resin is main adhesion wear and fatigue wear^[39], and the addition of CNTs can restrain the plastic deformation and adhesion of epoxy matrix in sliding against the steel. Subsequently, the epoxy/CNTs nanocomposites show decreased adhesion wear and improved wear resistance.

CONCLUSIONS

A novel noncovalent strategy was employed to disperse CNTs in various solvents using aniline trimer as a dispersant. The epoxy/CNTs nanocomposites were prepared *via* curing reaction of epoxy resin, Jeffamine D230 and AT-functionalized CNTs. Investigation of morphologies of the epoxy/CNTs nanocomposites *via* SEM and TEM gave the evidences for well dispersed CNTs in the epoxy matrix. The incorporation of CNTs into the epoxy resin enhanced the mechanical properties as well as the tribological performance of the as-prepared composites, which was attributed to the good dispersion, strong mechanical properties and self-lubricating effect of the CNTs.

REFERENCES

- 1 Thostenson, E.T., Ren, Z.F. and Chou, T.W., *Compos. Sci. Technol.*, 2001, 61(13): 1899
- 2 Moniruzzaman, M. and Winey, K.I., *Macromolecules*, 2006, 39(16): 5194
- 3 Coleman, J.N., Khan, U., Blau, W.J. and Gun'ko, Y.K., *Carbon*, 2006, 44(9): 1624
- 4 Mittal, G., Dhand, V., Rhee, K.Y., Park, S.J. and Lee, W.R., *J. Ind. Eng. Chem.*, 2015, 21: 11
- 5 Lakouraj, M.M., Rahpaima, G. and Zare, E.N., *Chinese J. Polym. Sci.*, 2014, 32(11): 1489
- 6 Chen, J., Xu, Y., Zheng, Y., Dai, L. and Wu, H., *Comptes Rendus Chimie*, 2008, 11(1-2): 84
- 7 Kalendová, A., Veselý, D., Sapurina, I. and Stejskal, J., *Prog. Org. Coat.*, 2008, 63(2): 228
- 8 Armelin, E., Alemán, C. and Iribarren, J.I., *Prog. Org. Coat.*, 2009, 65(1): 88
- 9 Breuer, O. and Sundararaj, U., *Polym. Compos.*, 2004, 25(6): 630
- 10 Zhang, B.Y., Ge, Q.S., Guo, Z.X. and Yu, J., *Chinese J. Polym. Sci.*, 2006, 34(8): 1032
- 11 Liu, T.X., Peng, H.D., Miao, Y.E., Tjiu, W.W., Shen, L. and Wei, C., *Chinese J. Polym. Sci.*, 2014, 32(7): 1276
- 12 Wang, Z.K., Hu, Q.L. and Cai, L., *Chinese J. Polym. Sci.*, 2010, 28(5): 801
- 13 Sahoo, N.G., Rana, S., Cho, J.W., Li, L. and Chan, S.H., *Prog. Polym. Sci.*, 2010, 35(7): 837
- 14 Spitalsky, Z., Tasis, D., Papagelis, K. and Galiotis, C., *Prog. Polym. Sci.*, 2010, 35(3): 357
- 15 Xie, X., Mai, Y. and Zhou, X., *Mater. Sci. Eng. R.*, 2005, 49(4): 89
- 16 Zhao, D., Li, Z., Liu, L., Zhang, Y., Ren, D. and Li, J., *Acta Chimica Sinica* (in Chinese), 2014, 72(2): 185
- 17 Brožová, L., Holler, P., Kovářová, J., Stejskal, J. and Trchová, M., *Polym. Degrad. Stab.*, 2008, 93(3): 592
- 18 Kharitonov, A.P., Simbirtseva, G.V., Tkachev, A.G., Blohin, A.N., Dyachkova, T.P. and Maksimkin, A.A., *Compos. Sci. Technol.*, 2015, 107: 162
- 19 Jiang, C., Zhang, J., Lin, S., Ju, S. and Jiang, D., *Compos. Sci. Technol.*, 2015, 118: 269
- 20 Weidt, D. and Figiel, Ł., *Compos. Sci. Technol.*, 2015, 115: 52
- 21 Vaisman, L., Wagner, H.D. and Marom, G., *Adv. Colloid Interface*, 2006, 128: 37
- 22 Yuan, W., Feng, J., Judeh, Z., Dai, J. and Chan-Park, M.B., *Chem. Mater.*, 2010, 22(24): 6542
- 23 Luan, J., Zhang, A., Zheng, Y. and Sun, L., *Compos. Part A-Appl. S.*, 2012, 43(7): 1032
- 24 Wang, T., Yuan, L., Liang, G. and Gu, A., *Appl. Surf. Sci.*, 2015, 359: 754
- 25 Yu, Z., Di, H., Ma, Y., Lv, L., Pan, Y. and Zhang, C., *Appl. Surf. Sci.*, 2015, 351: 986
- 26 Shen, X.J., Pei, X.Q., Liu, Y. and Fu, S.Y., *Compos. Part B-Eng.*, 2014, 57: 120

- 27 Gu, L., Liu, S., Zhao, H.C. and Yu, H.B., *ACS Appl. Mater. Inter.*, 2015, 7(32): 17641
- 28 Gu, L., Liu, S., Zhao, H.C. and Yu, H.B., *RSC Adv.*, 2015, 5(69): 56011
- 29 Wang, Z., Color, A.D., Guo, H.A., Kim, H., Park, C.L. and Hahn, H.T., *Mater. Res.*, 2012, 15(4): 510
- 30 Weng, C.J., Chang, C.H., Peng, C.W., Chen, S.W., Yeh, J.M. and Hsu, C.L., *Chem. Mater.*, 2011, 23(8): 2075
- 31 Brostow, W., Chonkaew, W., Menard, K.P. and Scharf, T.W., *Mater. Sci. Eng. A.*, 2009, 507(1-2): 241
- 32 Hao, Y., Liu, F. and Han, E.H., *Prog. Org. Coat.*, 2013, 76(4): 571
- 33 Ma, Y., Di, H., Yu, Z., Liang, L., Lv, L. and Pan, Y., *Appl. Surf. Sci.*, 2016, 360: 936
- 34 Ye, S., Feng, J. and Wu, P., *J. Mater. Chem. A.*, 2013, 1(10): 3495
- 35 Adhikari, A., Claesson, P., Pan, J., Leygraf, C., Dédinaité, A. and Blomberg, E., *Electrochim. Acta*, 2008, 53(12): 4239
- 36 Baughman, R.H., Zakhidov, A.A. and Heer, W.A., *Science*, 2002, 297: 787
- 37 Wang, R., Ayanan, S., Muthkrishnan, S. and Venkatachari, G., *Electrochim. Acta*, 2006, 51(28): 6313
- 38 Wang, Q.H., Xue, Q.J. and Shen, W.C., *Tribol. Int.*, 1997, 30: 193
- 39 Jacobs, O., Xu, W., Schädel, B. and Wu, W., *Tribol. Lett.*, 2006, 23(1): 65